Electro-optic dual-comb vibrometry

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Abstract: We use an ultrafast electro-optic dual comb interferometer to perform single-point vibrometry on the submillisecond time scale. As an example, we resolve the vibration of an ultrasound speaker driven at 50 kHz, achieving a sub-nanometer axial resolution through a measurement of the optical phase carrier.

OCIS codes: (320.7100) Ultrafast measurements; (120.6200); Spectrometers and spectroscopic instrumentation; (060.0060) Fiber and optical communications

1. Introduction

Dual-comb spectroscopy (DCS) is a precision technique that utilizes two frequency comb generators to measure spectroscopic samples in amplitude and phase [1]. The distinctive advantage of DCS is its ability of resolving individual comb lines. Beyond spectroscopy, dual-comb systems have found diverse applications in e.g. optical arbitrary waveform characterization [2, 3], coherent Raman spectral imaging [4] or light ranging and detection (LIDAR) [5]. In the latter case, the use of two phase-locked femtosecond frequency combs has demonstrated nanometer resolution for unambiguity ranges of > 1 m at measurement speeds of tens of milliseconds. This level of precision is achieved by the combination of pulse time-of-flight (TOF) information with an interferometric measurement based on the optical phase difference between the return and the reference pulses. In addition, if the combs are fully referenced, absolute distances can be measured. These outstanding achievements are possible thanks to state-of-the-art optical frequency comb technology. For applications less demanding in terms of resolution, dual-comb LIDAR can be dramatically simplified in hardware by using free-running femtosecond fiber lasers, but at the expense of limiting the system performance to the TOF measurements (i.e. micrometer precision on a time scale slightly below the millisecond [6]).

Electro-optic (EO) dual comb interferometry is a DCS modality where the combs are generated by external modulation of a continuous wave (cw) laser [7]. This kind of dual-comb system yields repetition rates exceeding 10 GHz and since the combs are fed by the same cw laser, the phase locking is guaranteed. EO dual-comb spectrometers have been used for rapid and sensitive detection of complex spectra across the near infrared region [8, 9]. We have recently optimized an EO dual-comb system operating at 100 MHz refresh rate and over > 1 THz bandwidth. [3]. However, despite the prospects of EO dual-comb spectrometers to measure ultrafast dynamic samples, most systems reported so far have been limited to static spectroscopic samples. Here, we show that our ultrafast EO dual-comb system is well matched for laser ranging of rapid vibrating targets whose axial displacement lies within the unambiguity range offered by EO combs (~1 cm at a repetition rate of ~10 GHz). As a proof of concept, we resolve the movement of an ultrasound speaker vibrating at 50 kHz. The inherent mutual coherence between the combs enables realizing an interferometric measurement that provides a precision of 6.3 mrad, equivalent to an axial displacement of 0.77 nm, at an effective measurement rate of ~250 kHz set by the averaging window.

2. Experimental setup and results

The experimental setup (Fig. 1) is a fiber Mach–Zehnder interferometer that includes two electrooptic frequency comb generators (signal and local oscillator, LO) and a balanced detector (BD) connected to a real-time oscilloscope (bandwidth of 16 GHz, sampling rate of 50 Gs/s). The comb generators operate at ~25 GHz and the frequency offset is δf =100 MHz. This offset leads to a heterodyne interference between the spectral components of both combs. In the time domain, the BD generates an interference signal that is a sequence of interferograms, each one containing a complete cross-correlation between the signal and the LO electric fields. The spectrum of every interferogram is an rf comb where the optical spectral information of a sample is encoded. By recovering the complex amplitude of the sample, the signal electric field can be reconstructed. To ensure an unambiguous frequency downconversion to the rf domain, an acousto-optic modulator (AOM) operating at 25 MHz is inserted in one interferometer arm to shift the central wavelength of the corresponding comb [3], increasing the duration of a single interferogram to 40 ns. In our laser ranging system, we have used two different vibrating examples. The first one is an all-fiber configuration, where the signal arm is split in two paths, one of which contains a fiber stretcher as a vibrating element (Fig. 1b). This component can introduce considerable delays (~ 1ps) in response to a dynamic voltage (maximum speed at 20 kHz). The second setup includes in the signal arm a circulator and a free-space stage formed by a PC collimator (which produces an internal reflection) and a piezo-speaker that can work at 50 kHz (Fig. 1c). In both systems, two train of pulses (the reference and the target) are created and the delay τ between them changes due to the sinusoidal voltage applied to the vibrating element.

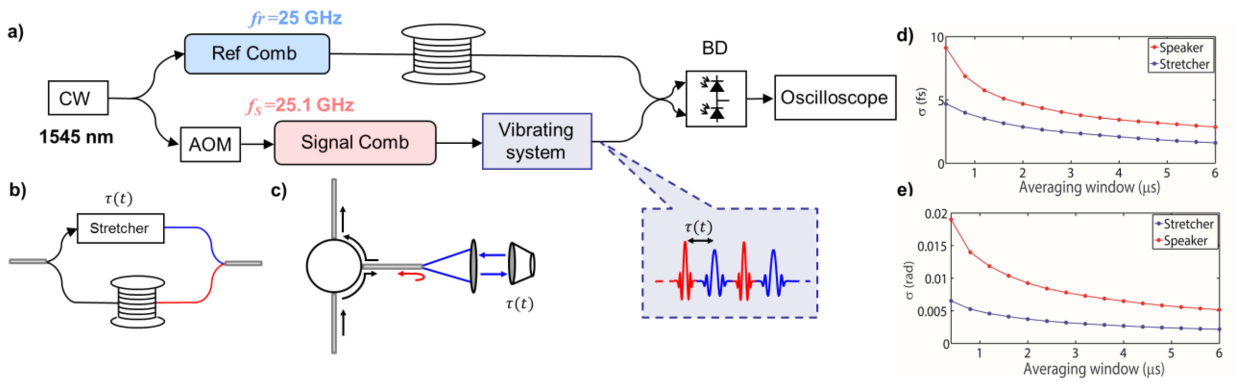

Fig. 1: a) Simplified experimental setup, b) All-fiber vibrating system, c) Setup for measuring the vibrations of a speaker, d) Relative timing jitter between the reference and the target for different averaging windows and e) Phase jitter of the interferometric measurement for different averaging windows.

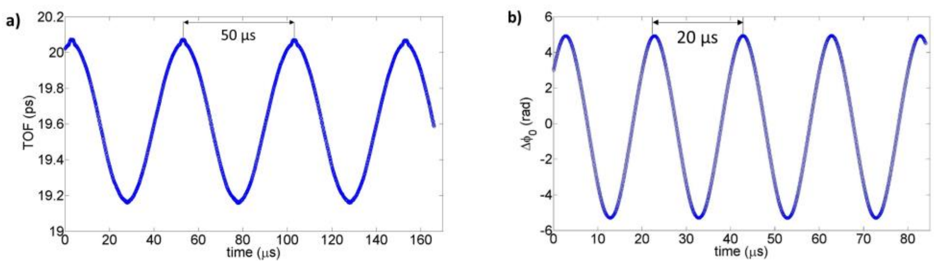

Fig. 2: a) TOF measurements for the stretcher and b) Change in the interferometric phase term ϕ_0 due to the vibration of the speaker.

To resolve the induced time-dependent delay, the contributions to the signal electric field of the reference and target pulses are time-windowed and Fourier transformed for each interferogram. The relative spectral phase ϕ between the two separated contributions is represented versus the relative optical frequency $\nu - \nu_0$, where ν_0 is the frequency of the optical carrier. A linear fit $\phi(\nu) = \phi_0 + m(\nu - \nu_0)$ provides a TOF measurement of τ through the slope m, which is related to the time shift between the reference and target pulses. On its turn, the optical phase difference between the reference and target, ϕ_0, enables a high-resolution interferometric measurement within a limited unambiguity range (half the carrier wavelength) [5]. The precision of the TOF measurement is ultimately limited by the timing jitter of the retrieved signal pulses, whereas the phase jitter of the cw laser determines the precision of the interferometric term ϕ_0. We evaluated these as a function of the averaging window for a dc applied voltage (static sample). For an averaging window of 4 μs the relative timing jitter between the reference and target was 2.1 fs (Fig. 1d). This is equivalent to 0.43 μm precision in TOF. The phase jitter amounts to 6.3 mrad for the same averaging window, equivalent to a precision of 0.77 nm (Fig. 1e). For the stretcher, the relative delays are long and the TOF is enough (see Fig. 2a). The ultrasound speaker however introduces nanometer variation which are only resolvable through the interferometric phase term ϕ_0. Taking 194.09 THz for the carrier frequency and considering a refractive index in air of 1.00027, Fig. 2b reveals minute nanometer vibrations in a time scale of a few μs.

3. References

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